Scalable MLFMA Code for Single And Multiple Targets over a Half Space

CHSSI CEA-9

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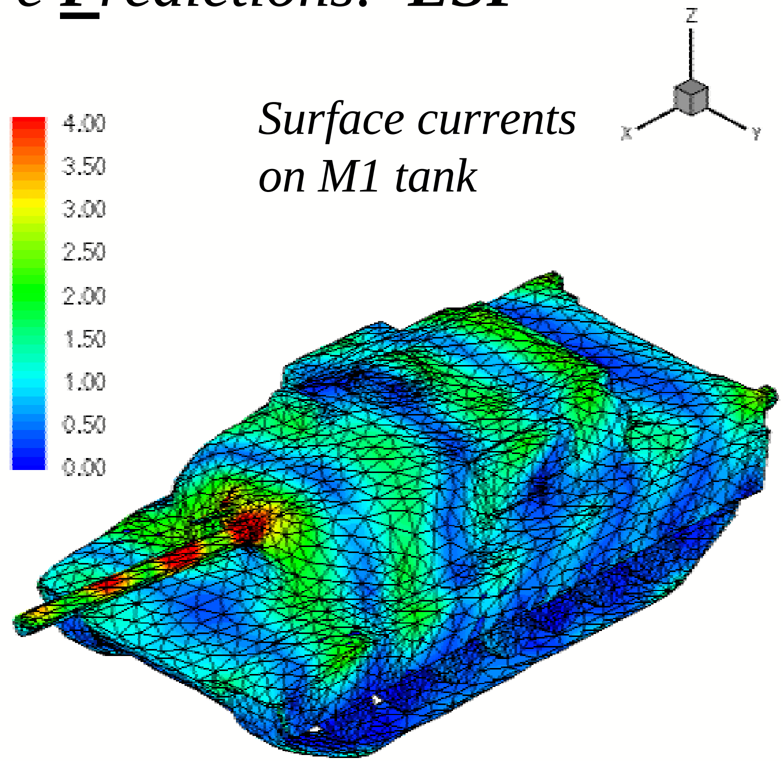
CEA-9: Electromagnetic Sensing of Surface and Subsurface Targets: Simulation and Signal Processing

"***E****lectromagnetic* ***S****ignature* ***P****redictions:* ***ESP***"

- Synopsis
  - ***Objective***: **Develop scalable MoM and MLFMA software for simulating radar scattering from targets in/above soil (mines, UXO, vehicles, bunkers, trees, etc.). Use results of EM models to train physics-based signal processing algorithms (e.g. Hidden Markov Model)**
  - ***Partners:*** **Duke University and ARL**
  - ***Development Paradigm***: **FORTRAN 90; C; MPI; X-windows GUI , Python**



- ***Performance Goals***
  - **Alpha Review completed 19 Oct 2001**
  - **Beta Review scheduled 4QFY02**
  - ***Operating Platforms***: **IBM SP-P3, SGI O2k, Linux clusters**
  - ***Scalability goal***: **50% speedup on 128 processors**
  - ***Threshold:*** **40% speedup on 64 processors**

- ***Management***
  - ***CHSSI***: **$500k/year – for 3 years**
  - ***Leveraging:*** **$500k/yr (ARO & SERDP), $6M demining MURI (5 yrs)**
  - ***Transition Approach***: **Serial MoM and MLFMA codes routinely employed by ARL & NVESD**

Outline

- Brief review of Method of Moments (MoM) and Multi-Level Fast-Multipole Algorithm (MLFMA) for single target above a lossy half space (soil); scalable formulation

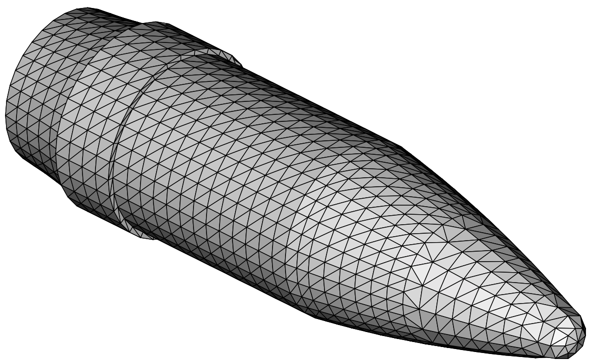
- Extension to an arbitrary number of targets in the presence of a half space

  - Target under trees

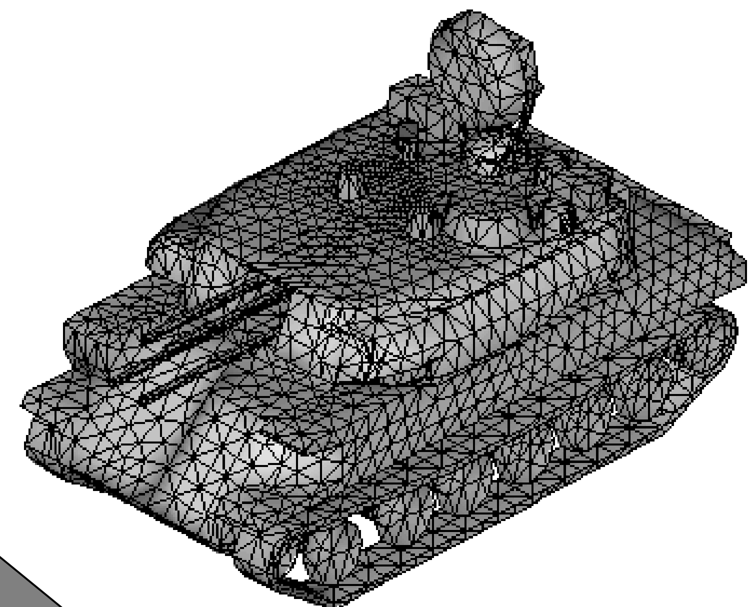
  - Propagation through foliated terrain

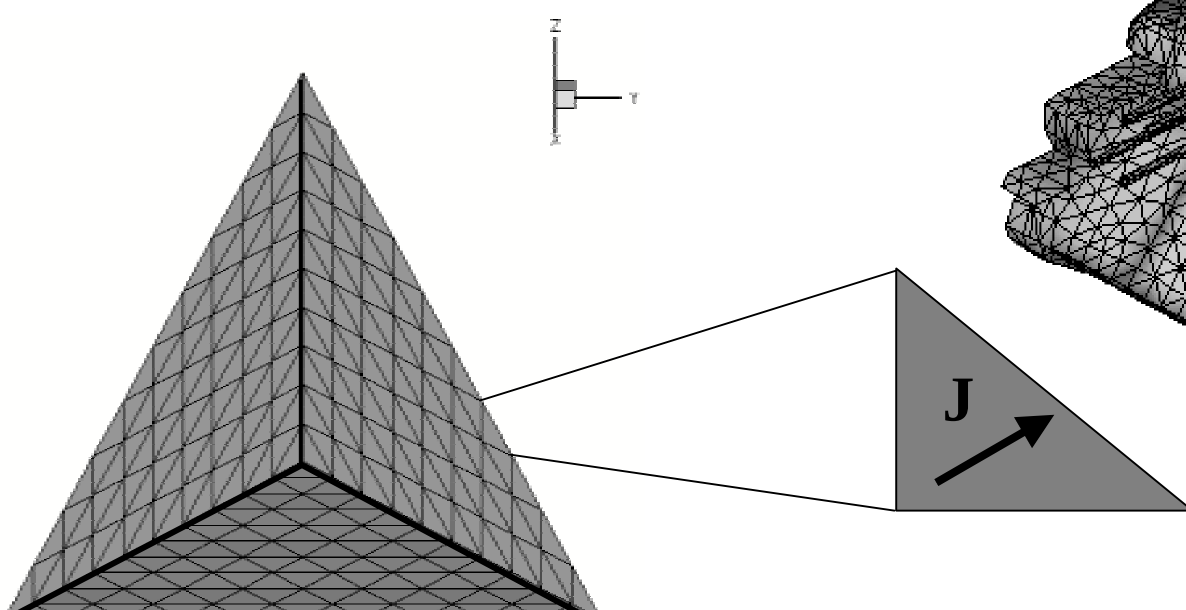
- Summary

MLFMA/MoM – Review



*As in all such problems, numerical challenge is calculation of the electric surface currents (**J**) on the target surface*





Governing Equations

- Boundary condition for perfect conductor:

$$\mathbf{E}_{\tan} = 0$$

- Total field expressed as:

$$\mathbf{E}_{\tan} = [\,\mathbf{E}^{\mathrm{inc}} + \mathbf{E}^{\mathrm{s}}\,]_{\tan} \quad \Rightarrow \quad -\mathbf{E}^{\mathrm{s}} = \mathbf{E}^{\mathrm{inc}}$$

- Using the equivalence principle:

$$j\omega\mu \iint_S \overset{\tau}{\mathbf{K}} \cdot \mathbf{J}\,ds' + \frac{j}{\varepsilon\omega} \nabla \iint_S \mathrm{K}_e \nabla' \cdot \mathbf{J}\,ds' = \mathbf{E}_{\tan}^{\mathrm{inc}}$$

$$[\mathbf{Z}][\mathbf{J}] = [\mathbf{E}^{\mathrm{inc}}]$$

Review of the Method of Moments (cont.)

Solving: $\left[\mathbf{Z}\right]\left[\mathbf{J}\right] = \left[\mathbf{E}^{\text{inc}}\right]$

1. Direct solver using LU decomposition : $O(N^3)$

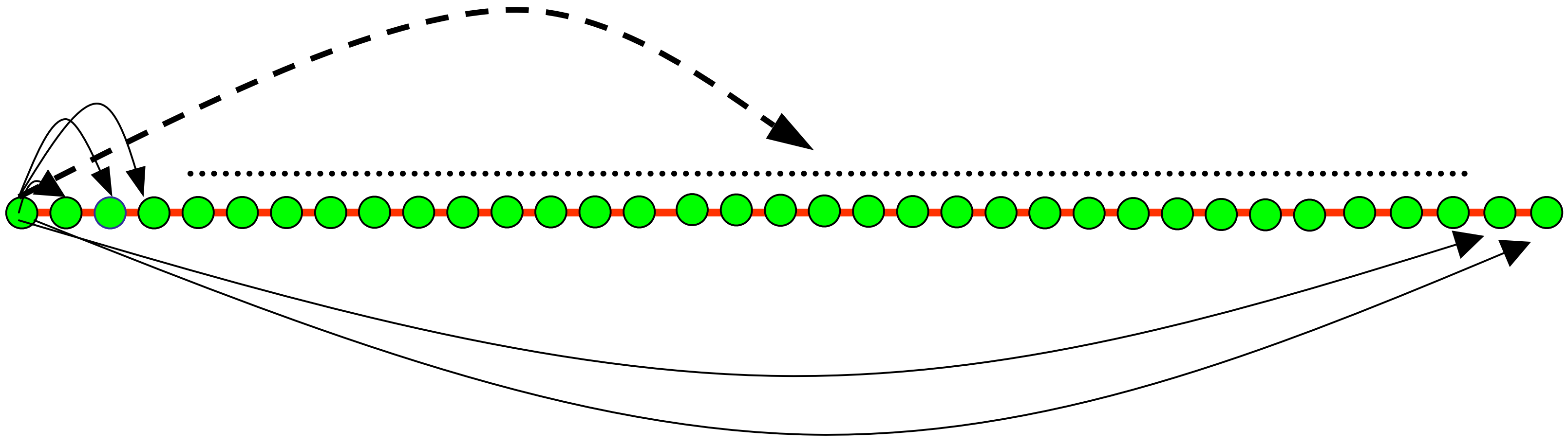
2. Iterative solver (CG) for the linear equations: $O(P \cdot N^2)$

3. Store impedance matrix needs RAM: $O(N^2)$

Our VHF T-72 tank model has 12087 unknowns $\Rightarrow$ 2.2 GBytes RAM

Looking at Impedance Matrix: **Z**

MoM: individual interaction between
basis function and testing function.

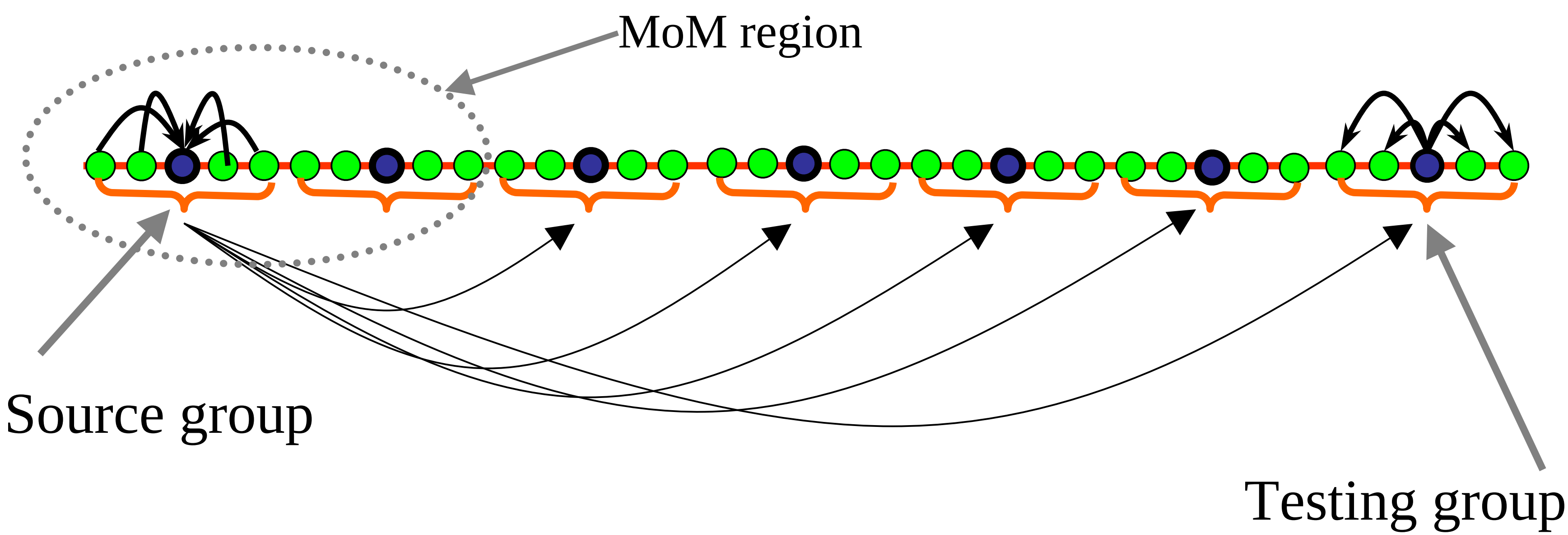


*Every basis function interaction with all the testing function.
Hence MoM has N^2 interactions and N^2 memory requirements.

From MoM to Fast Multipole Method (FMM)

MoM: individual interaction between testing function and basis function.

FMM: group interaction between testing group and source group for far interactions (near interaction still use MoM scheme)

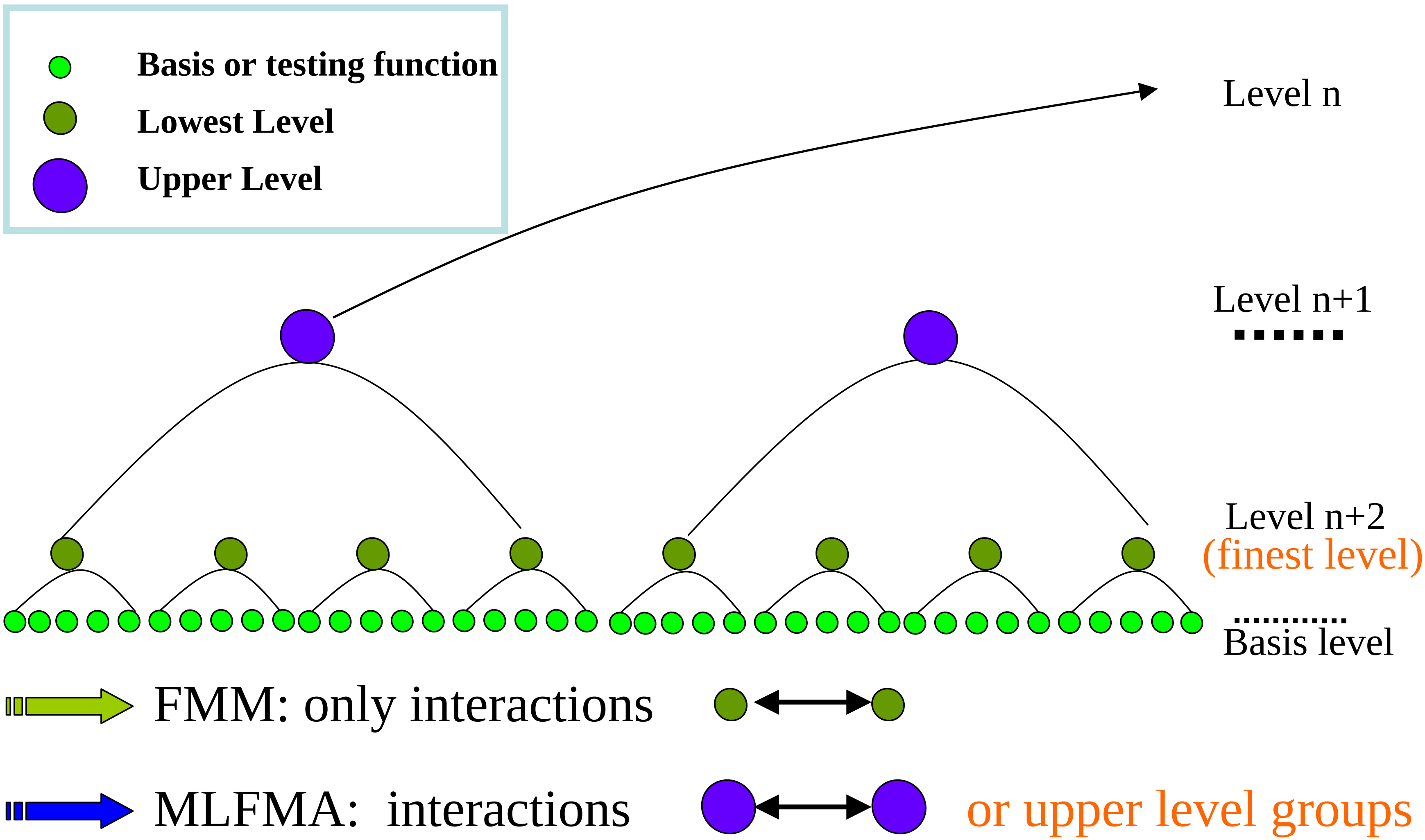


$$[\mathbf{Z}][J] = \{[\mathbf{Z}^{near}] + [\mathbf{Z}^{far}]\}[J]$$

diagonally dominant sparse matrix

handled by FMM on group-to-group basis

Multi-level Fast Multi-pole Algorithm (MLFMA)

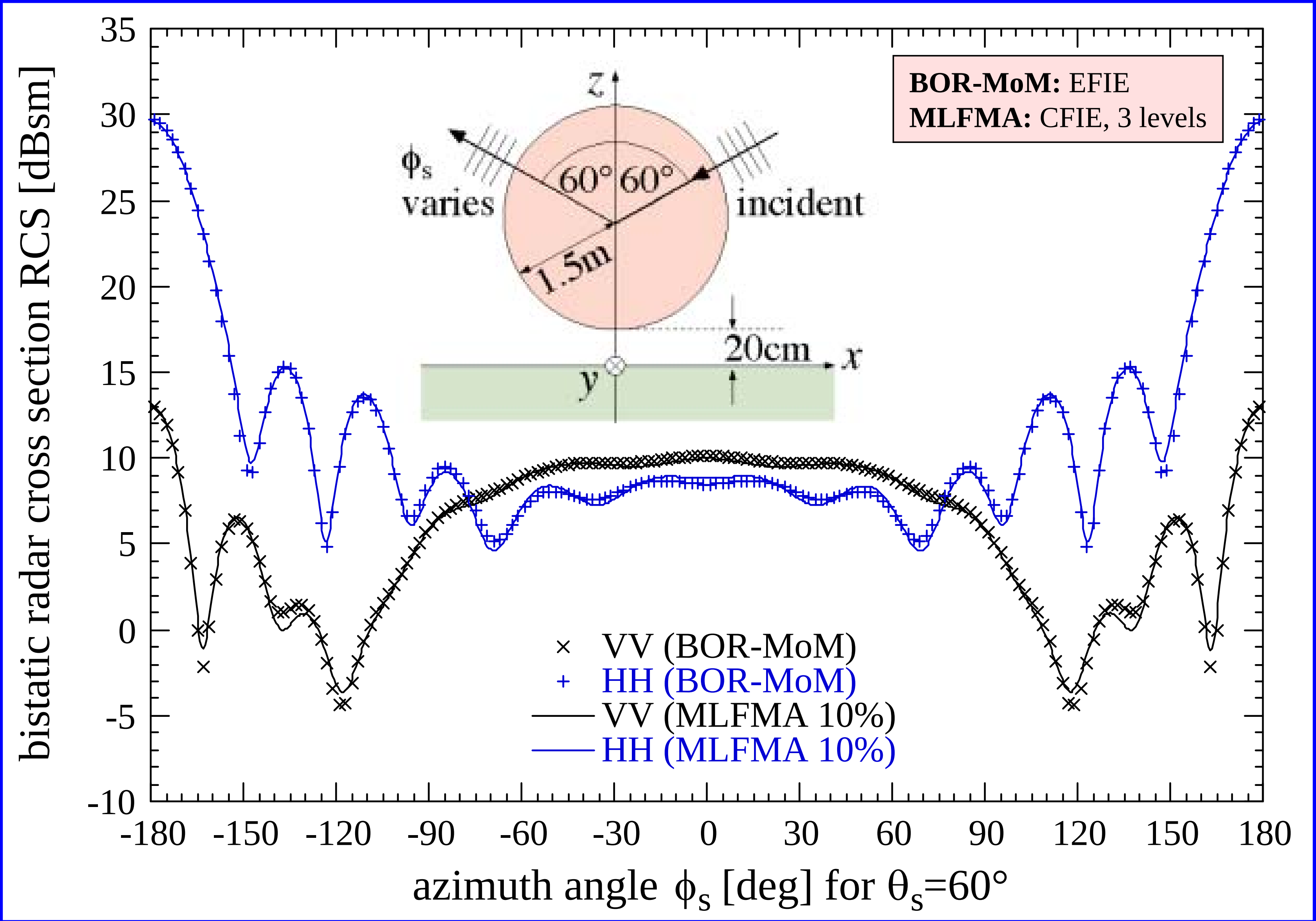


RAM and CPU for MoM, FMM & MLFMA

	RAM	CPU (CG solver)
MoM	$O(N^2)$	$O(P \cdot N^2)$
FMM	$O(N^{1.5})$	$O(P \cdot N^{1.5})$
MLFMA	$O(N \log N)$	$O(P \cdot N \log N)$

Bistatic RCS of Sphere ($2a=3\lambda$, N=9966) Above Soil

f=300MHz, a=1.5m, $\theta_i=60°$, $\phi_i=0°$, $\theta_s=60°$, Yuma soil: 10% water by weight



T72 Tank/450MHz target *N*=46,131 unknowns

SGI runs:

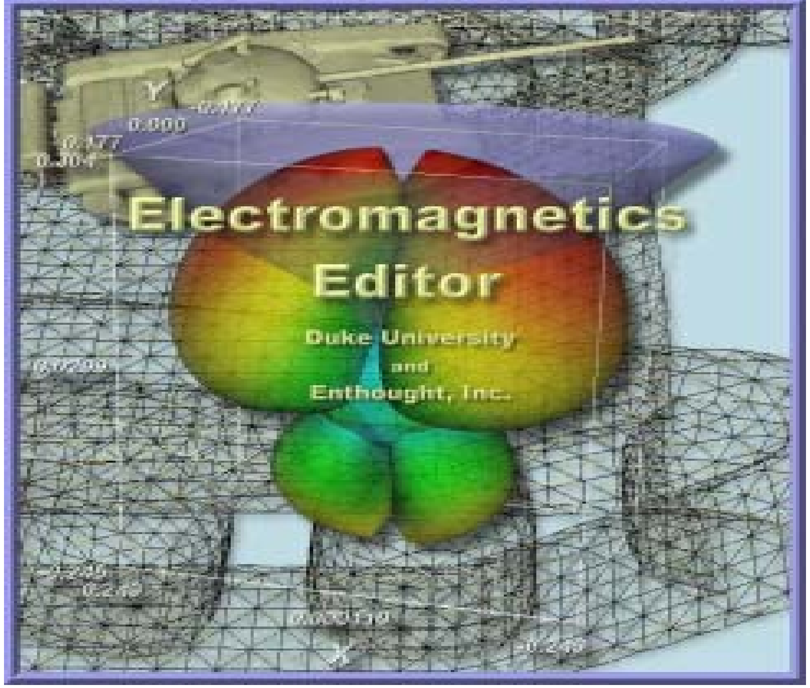
1 CPU	23999 sec	1.00 speed-up (= T_1/T_N)
2	18014	1.33
4	9065	2.65
8	3279	7.32
16	1947	12.32
32	1067	22.49
64	794	30.22

IBM runs:

4 CPUs	7241 sec	4.00 assumed speed-up
8	4651	6.23
16	2379	12.17
32	1581	18.32
64	1003	28.89

Beowulf cluster:

8 CPUs	4890
16	3802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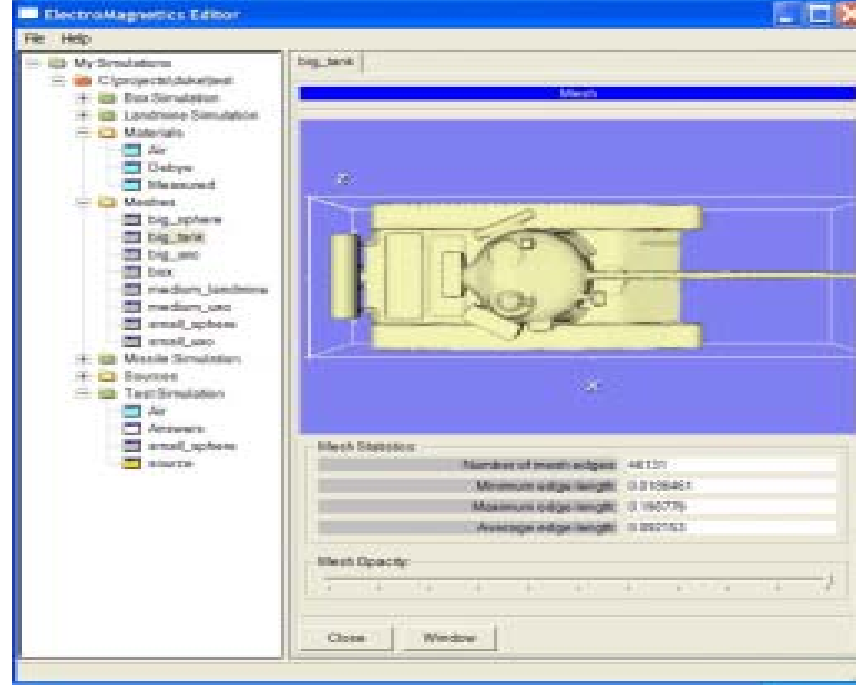
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source
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Maximum edge length
Average edge length
Mesh Opacity
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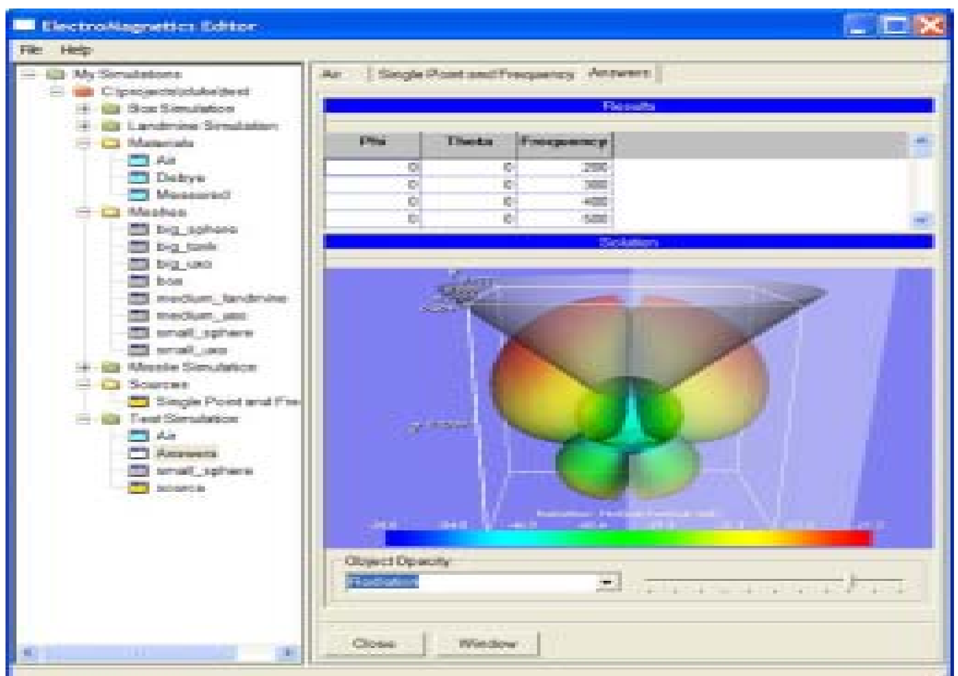
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Air
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Single Point and Frequency
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Theta
Frequency
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Object Opacity
Close
Window

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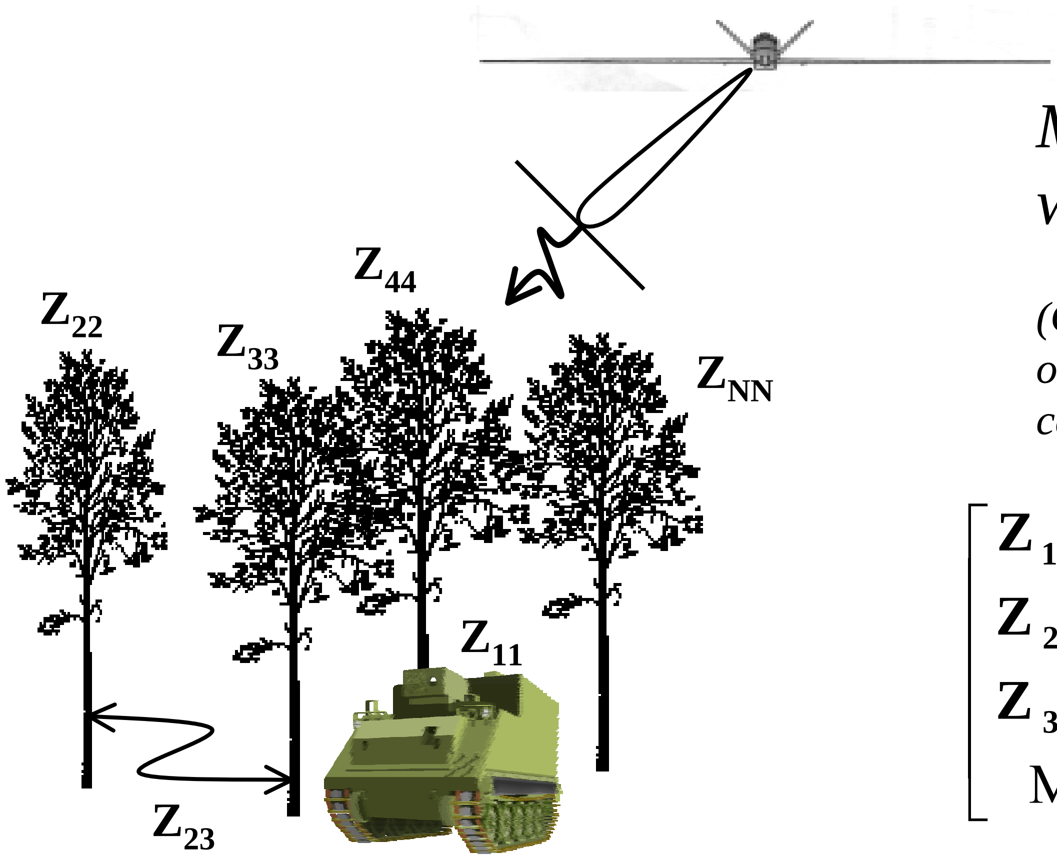
Modeling Multiple Targets – Uncoupled



MoM matrix grows as N^2 with each additional target.

(Given size of target and wideband frequencies of interest, problem size grows beyond the capabilities of even supercomputers.)

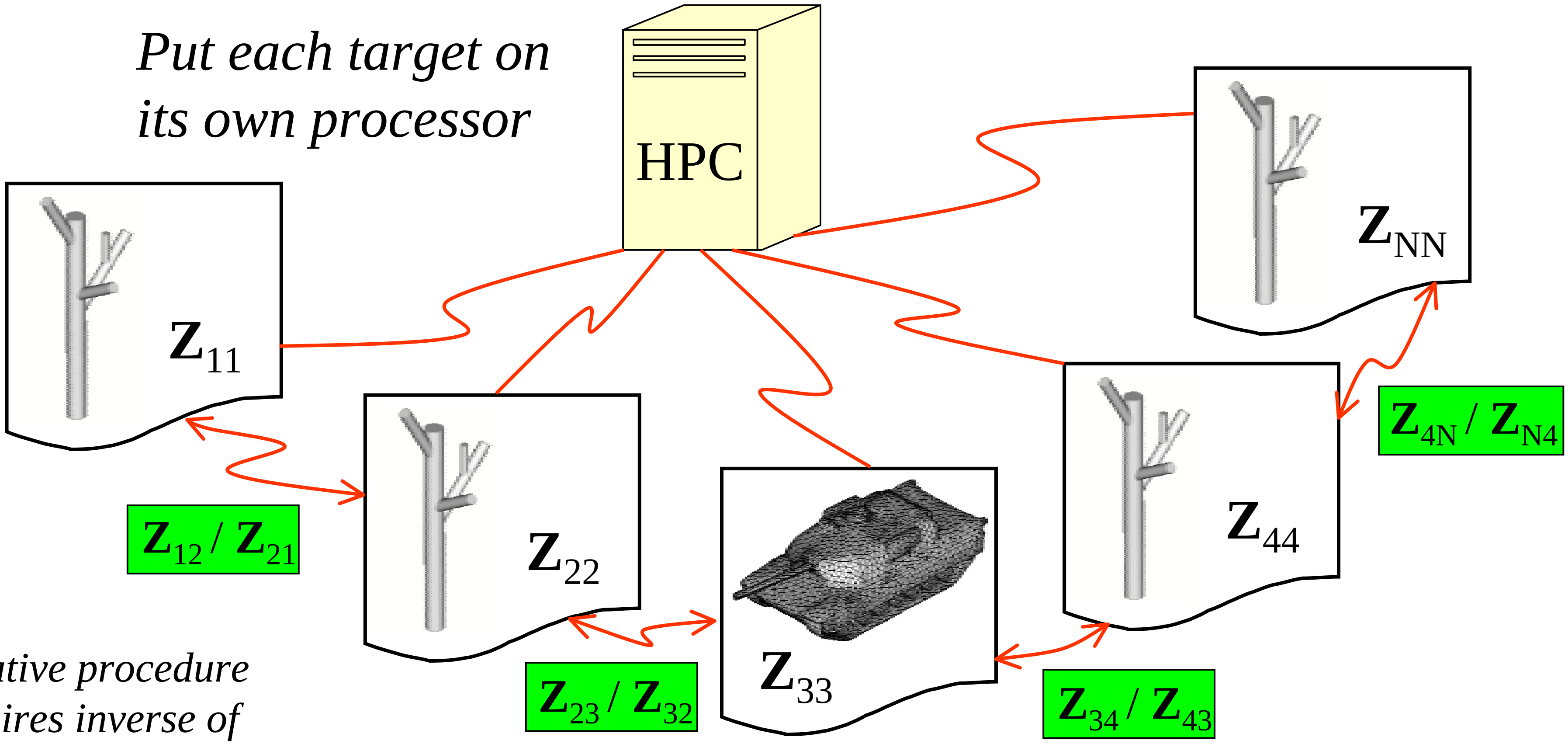
$$\begin{bmatrix} \mathbf{Z}_{11} & \mathbf{Z}_{12} & \mathbf{Z}_{13} & \Lambda \\ \mathbf{Z}_{21} & \mathbf{Z}_{22} & \mathbf{Z}_{23} & \Lambda \\ \mathbf{Z}_{31} & \mathbf{Z}_{32} & \mathbf{Z}_{33} & \Lambda \\ M & M & M & O \end{bmatrix} \begin{bmatrix} \mathbf{J}_1 \\ \mathbf{J}_2 \\ \mathbf{J}_3 \\ M \end{bmatrix} = \begin{bmatrix} \mathbf{E}_1 \\ \mathbf{E}_2 \\ \mathbf{E}_3 \\ M \end{bmatrix}$$

For weak coupling ($\mathbf{Z}_{ij} \approx 0$, $j \neq i$), an approximate simplified matrix can be written.

$$\begin{bmatrix} \mathbf{Z}_{11} & 0 & 0 & \Lambda \\ 0 & \mathbf{Z}_{22} & 0 & \Lambda \\ 0 & 0 & \mathbf{Z}_{33} & \Lambda \\ M & M & M & O \end{bmatrix} \begin{bmatrix} \mathbf{J}_1 \\ \mathbf{J}_2 \\ \mathbf{J}_3 \\ M \end{bmatrix} = \begin{bmatrix} \mathbf{E}_1 \\ \mathbf{E}_2 \\ \mathbf{E}_3 \\ M \end{bmatrix}$$

Modeling Multiple Targets – Coupled

Put each target on its own processor



Iterative procedure requires inverse of diagonal matrices only

$$\begin{bmatrix} \mathbf{Z}_{11} & \mathbf{Z}_{12} & \mathbf{Z}_{13} & \Lambda \\ \mathbf{Z}_{21} & \mathbf{Z}_{22} & \mathbf{Z}_{23} & \Lambda \\ \mathbf{Z}_{31} & \mathbf{Z}_{32} & \mathbf{Z}_{33} & \Lambda \\ \mathrm{M} & \mathrm{M} & \mathrm{M} & \mathrm{O} \end{bmatrix} \begin{bmatrix} \mathbf{J}_1 \\ \mathbf{J}_2 \\ \mathbf{J}_3 \\ \mathrm{M} \end{bmatrix} = \begin{bmatrix} \mathbf{E}_1 \\ \mathbf{E}_2 \\ \mathbf{E}_3 \\ \mathrm{M} \end{bmatrix} \Rightarrow$$

$$\begin{aligned} \mathbf{J}_1 &= \mathbf{Z}_{11}^{-1}\left\{\mathbf{E}_1 - \mathbf{Z}_{12}\mathbf{J}_2 - \mathbf{Z}_{13}\mathbf{J}_3 - \Lambda\right\} \\ \mathbf{J}_2 &= \mathbf{Z}_{22}^{-1}\left\{\mathbf{E}_2 - \mathbf{Z}_{21}\mathbf{J}_1 - \mathbf{Z}_{23}\mathbf{J}_3 - \Lambda\right\} \\ \mathbf{J}_3 &= \mathbf{Z}_{33}^{-1}\left\{\mathbf{E}_3 - \mathbf{Z}_{31}\mathbf{J}_1 - \mathbf{Z}_{32}\mathbf{J}_2 - \Lambda\right\} \\ \mathrm{M} &= \mathrm{M} \end{aligned}$$

Inter-Target Interactions

- For N_k basis functions on target k, and N_m on target m, direct computation of inter-target scattering is $O(N_k N_m)$

- Have employed the FMM to efficiently account for inter-target scattering

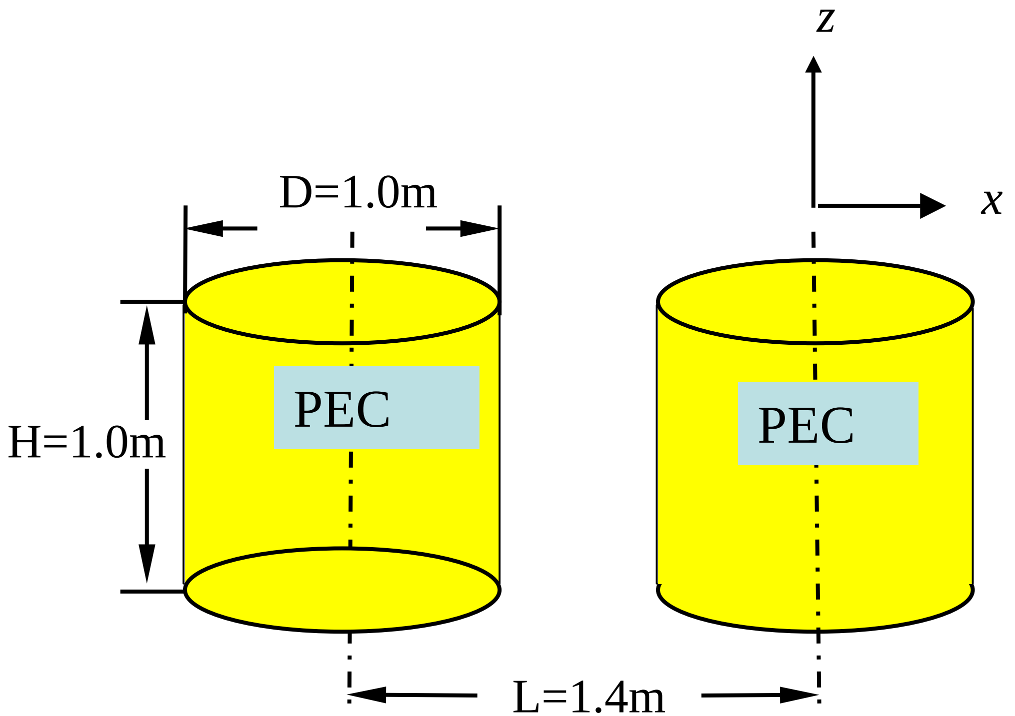
- For targets k and m, we utilize the largest FMM box (cluster) sizes that allows *all* interactions to be handled via “far” terms

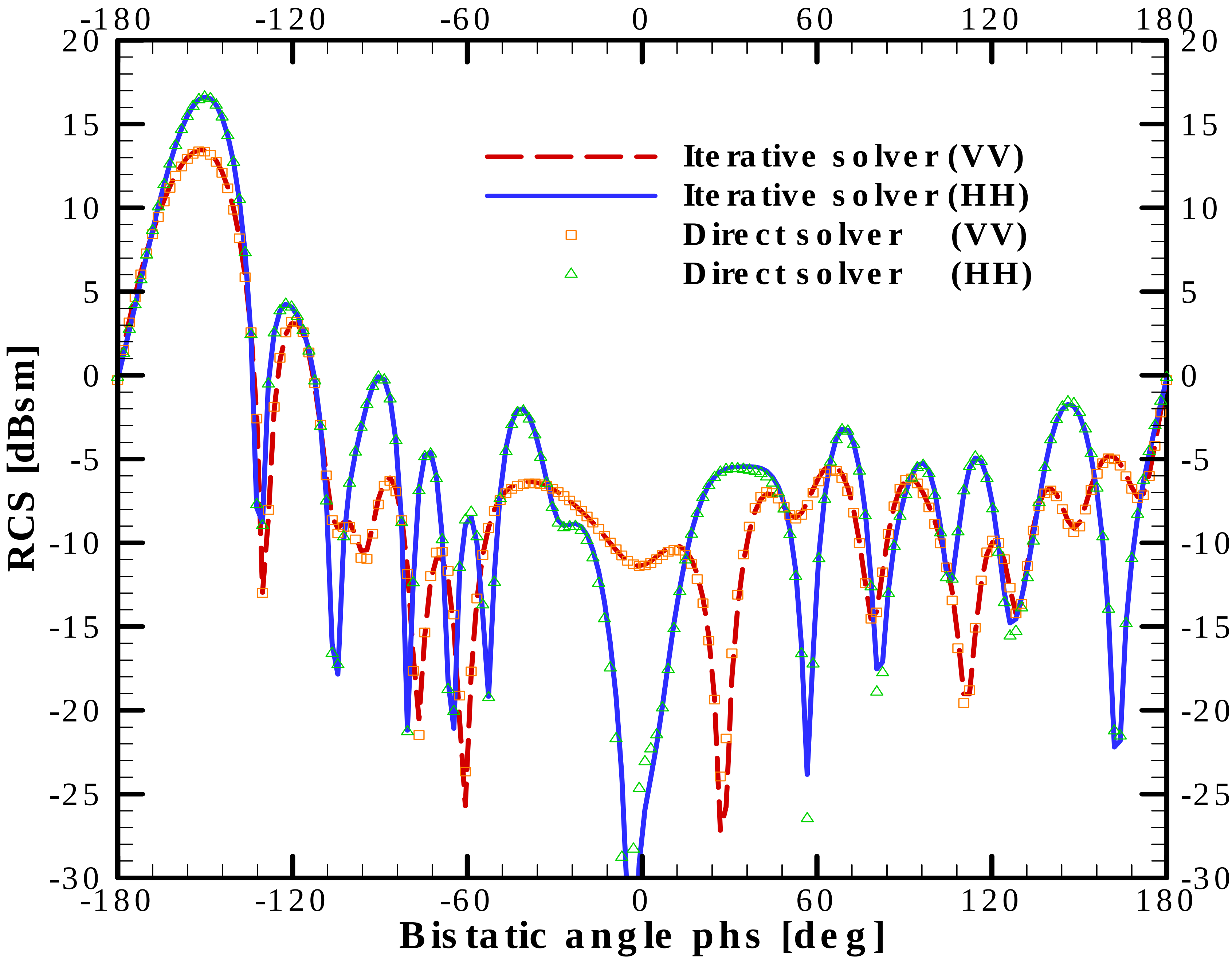
- Box sizes are target dependent and inter-target-distance dependent

- For targets separated further than nominal target sizes, each target placed within single FMM box

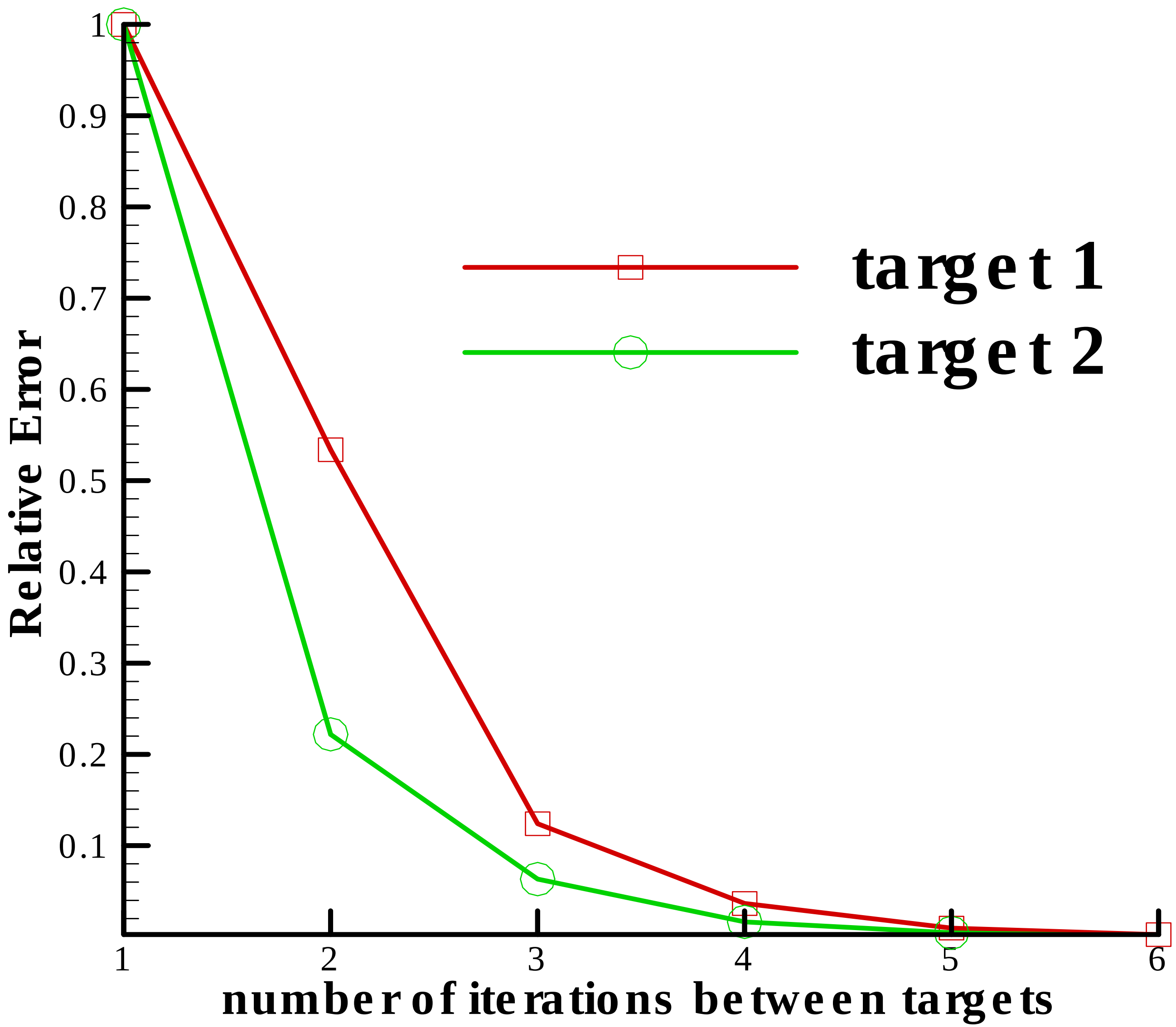
- Inter-target-scattering propagator communicated efficiently via MPI (each target on a separate computer node)

Freespace Targets





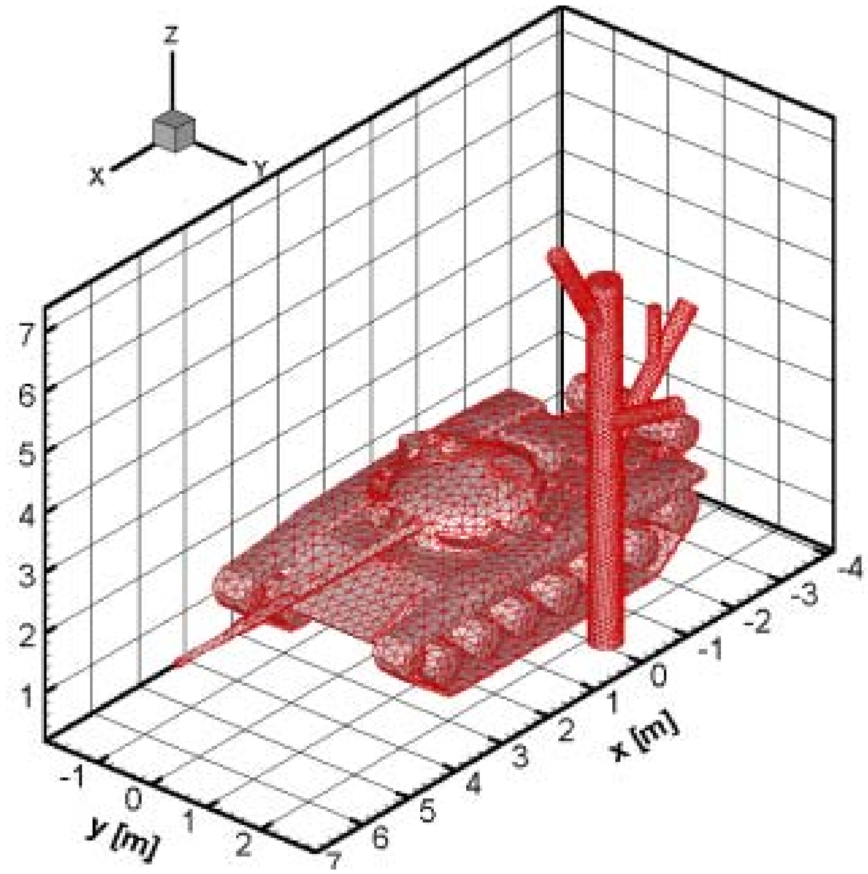
Iterative solver (VV)
Iterative solver (HH)
Direct solver (VV)
Direct solver (HH)
RCS [dBsm]
Bistatic angle phs [deg]
-180
-120
-60
0
60
120
180
20
15
10
5
0
-5
-10
-15
-20
-25
-30



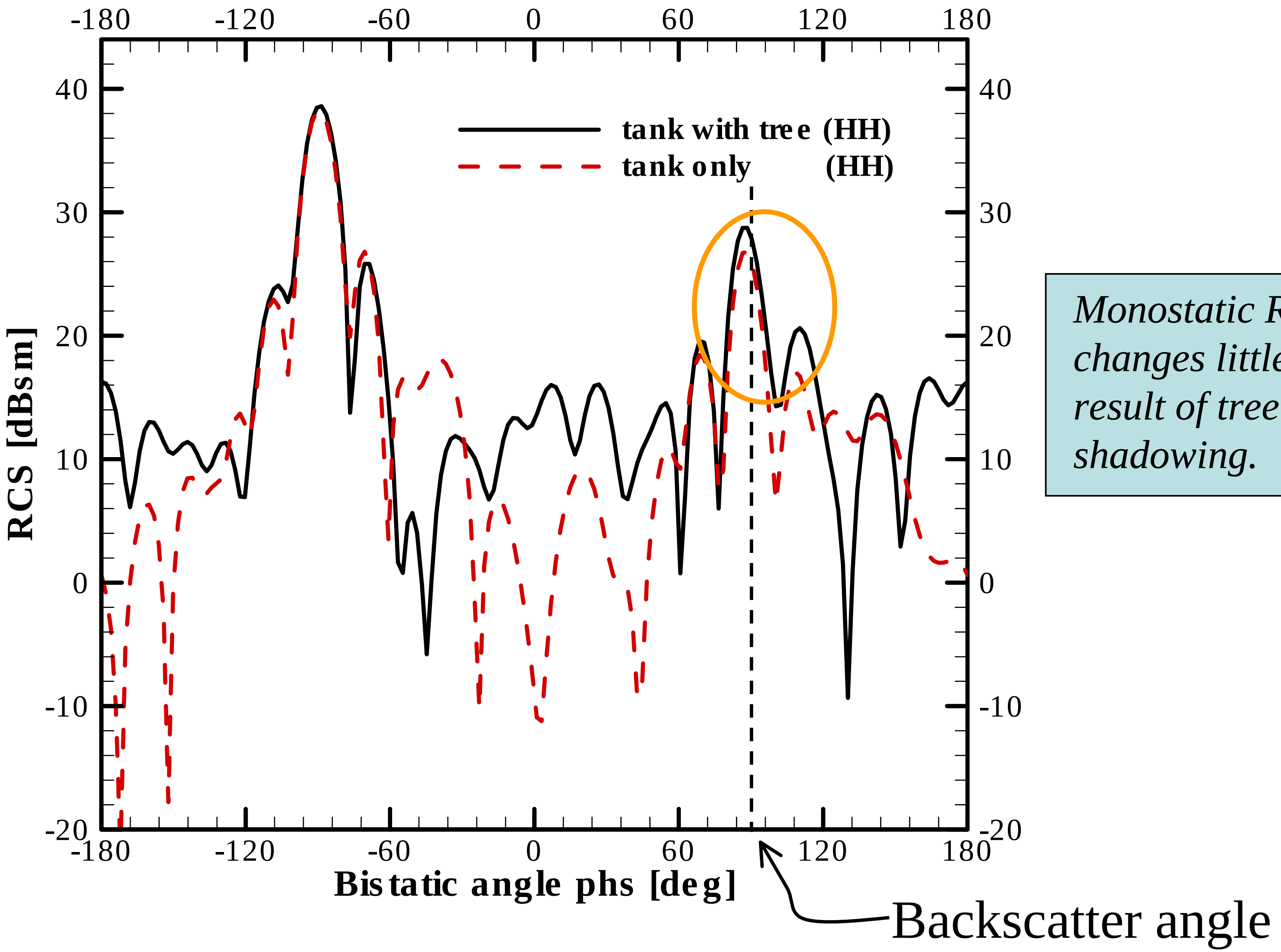
target 1
target 2
Relative Error
number of iterations between targets
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1
2
3
4
5
6

Coupled Model Over Half-Space

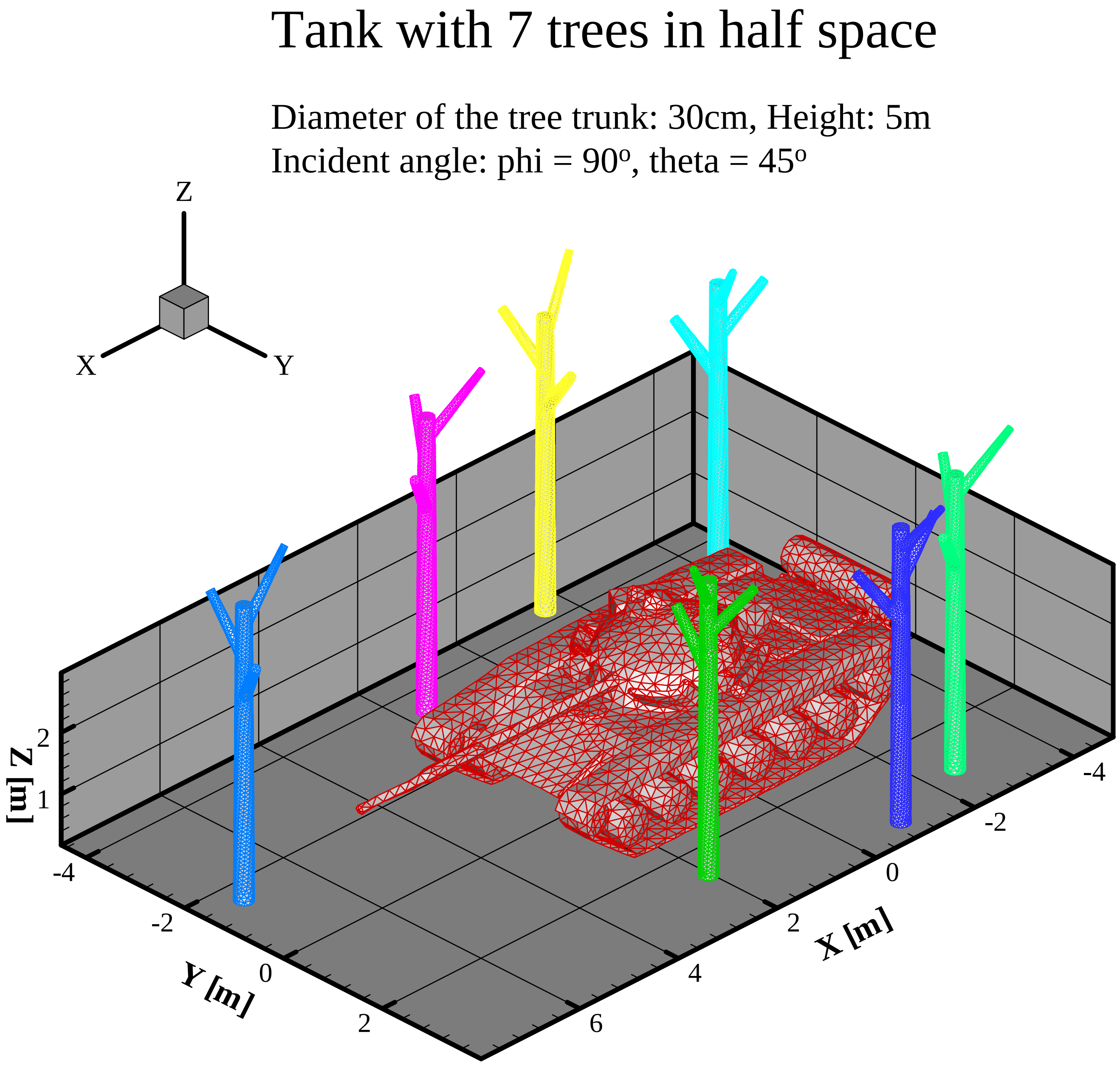
Tank, tree, and ground composite model:
Coupled – all interactions accounted for.
θ=45 degrees
φ=90 degrees (broadside)
frequency=300 MHz



Bistatic RCS of Tank vs. Tank and Tree: HH



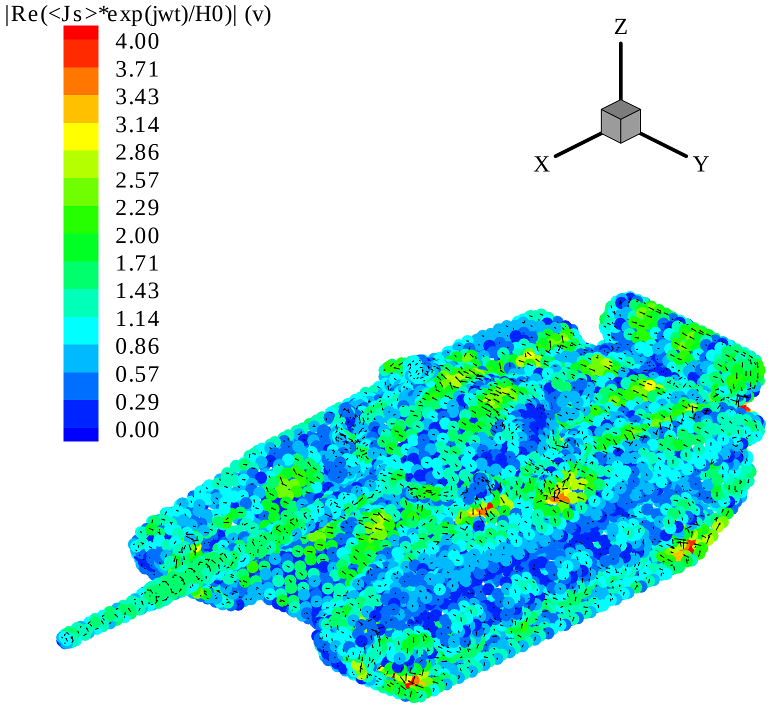
Monostatic RCS changes little as a result of tree shadowing.



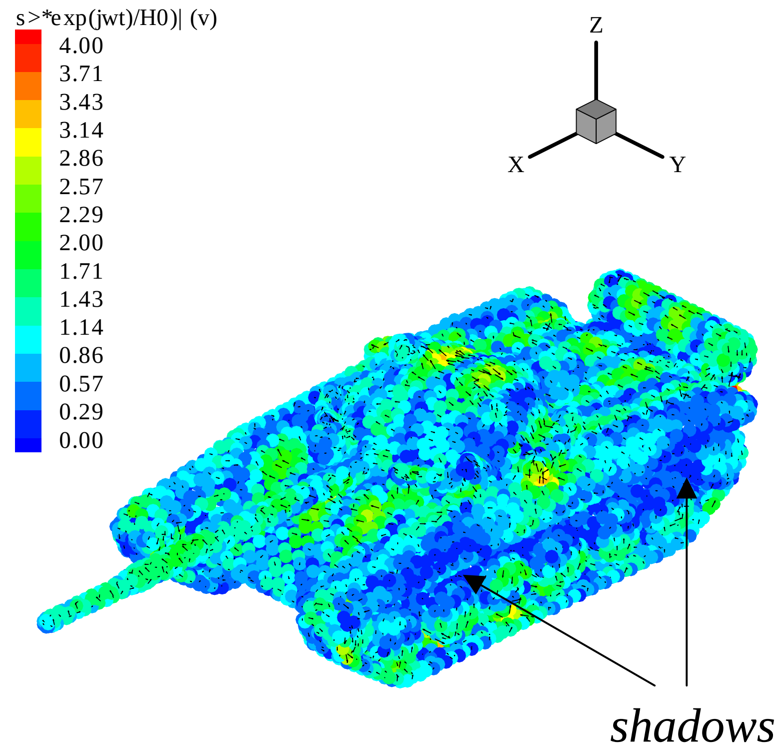
Tank with 7 trees in half space
Diameter of the tree trunk: 30cm, Height: 5m
Incident angle: phi = 90º, theta = 45º
Z
X
Y
Z [m]
1
2
-4
-2
0
2
Y [m]
6
4
2
0
-2
-4
X [m]

Current Distribution – Vpol

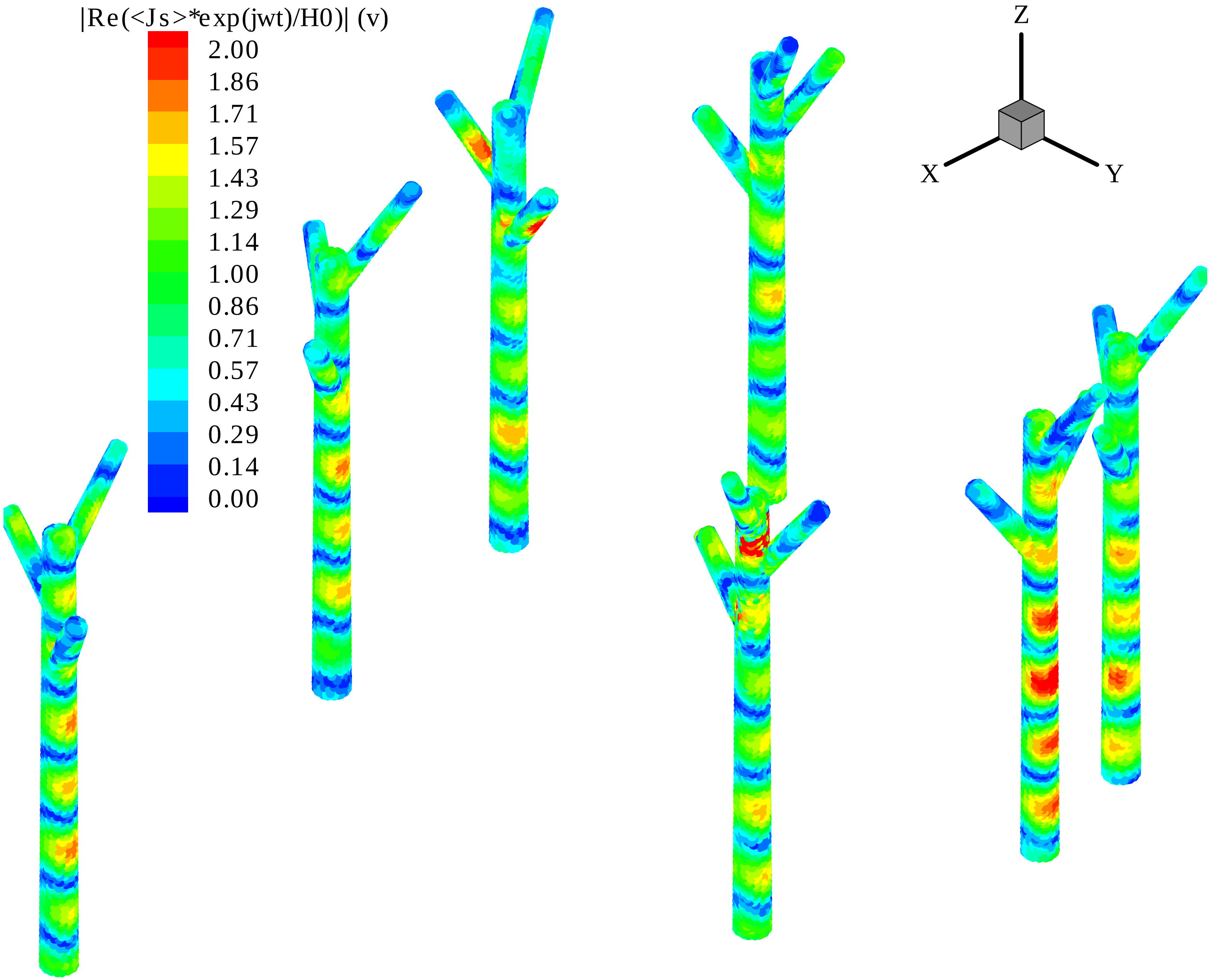
Isolated tank



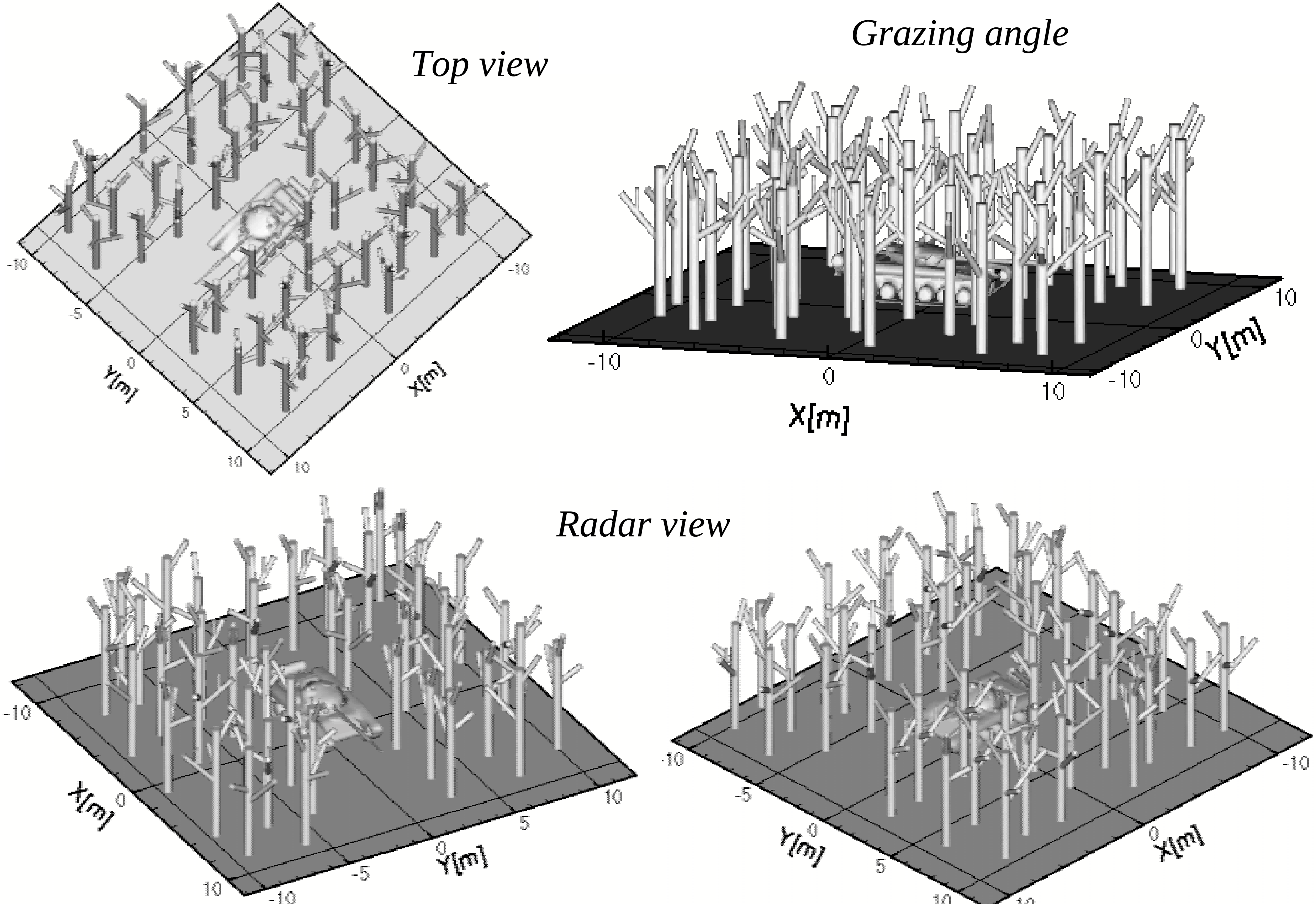
Tank with all trees present



Current distribution on trees - Vpol



Ultimately Want to get Here – SAR Forest Model



Summary

- Scalable MLFMA developed and tested for general PEC/dielectric targets above/below a half space

- Scalable software now capable of efficiently analyzing scattering from and propagation through an arbitrary number of dielectric/PEC targets in the presence of a half space

- Code can be modified to handle communications problem (e.g., antenna mounted on vehicle)

- Beta version of CEA-9 to be released this August
    - can visit the web site: **http://webtech.ee.duke.edu/cgi-bin/chssi/news**